SECTION 1. ADMINISTRATIVE INFORMATION

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Project title
Modeling Effects of Climate Change on Spruce-Fir Forest Ecosystems and Associated Priority Bird Populations

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September 1, 2013-September 30, 2015

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$218,000

SECTION 2. PUBLIC SUMMARY: Spruce-fir forests and associated bird species are recognized as some of the most vulnerable ecosystems and species to the impacts of climate change. This work capitalized on a rich suite of long-term data from these ecosystems to document recent trends in these forests and their associated bird species and developed tools for predicting their future abundance under climate change. Findings from this work indicate declining trends in the abundance of spruce-fir obligate birds, including Bicknell's Thrush, across the Lake States and New England. In contrast, montane spruce-fir forests in the White and Green Mountains of New England exhibited patterns of increasing abundance, potentially due to their recovery from the negative impacts of historic land use and pollution. Despite these recent trends, long-term predictions of future abundance for the dominant species found in spruce-fir forests (black, red, and white spruce and balsam fir) indicated large declines in these species from across much of the northeastern United States by the year 2090. Several areas were recognized where these forests might persist, including high elevation portions of NH, NY, and

VT and in large portions of northwestern ME. An understanding of these future dynamics is critical for informing and prioritizing conservation efforts aimed at protecting these ecosystems and associated wildlife species under future climate change and speak to the importance of sustaining long-term monitoring efforts to assist these decisions.

SECTION 3. PROJECT SUMMARY: Eastern spruce-fir forest ecosystems are among the most vulnerable to climate change within the coterminous US. The goal of this project was to develop tools to identify refugia sites most likely to support spruce-fir forest and its associated high-priority obligate spruce-fir bird species over the long-term under projected climate change scenarios. Specific research objectives included: (1) producing high-resolution (temporal and spatial) projections of spruce-fir forests, including stand characteristics like structure and composition; (2) estimating future changes in the distribution, productivity and stand characteristics of the spruce-fir forest type due to potential changes in climate; (3) comparing the distribution and condition of spruce-fir forest for different climate change scenarios to identify areas with key physiographic settings likely to support refugia for this forest type; (4) modeling bird occurrence, distribution, nesting phenology and productivity as functions of climate and these modeled values for forest structure and composition; (5) linking these bird-habitat models to projected climatic and forest conditions to predict future bird occurrence, distribution and nesting phenology and productivity across the region; and (6) identifying areas with the greatest richness of priority bird species across climate scenarios. These objectives were accomplished using long-term vegetation, bird, and remote sensing data from spruce-fir forests across the Northeast and Great Lakes regions to predict the future extent and condition of spruce-fir forests and associated avifauna. In particular, we combined 16 point count datasets, controlling for differences in protocol and detection probabilities to estimate regional trends for 14 spruce-fir forest bird species across the study region. In addition, 25 long-term vegetation datasets and Landsat imagery from 1991-2010 were used for developing species distribution models for predicting climate impacts on future habitat suitability for spruce-fir species and for evaluating recent dynamics in the location of the montane spruce-fir ecotone. Finally, maps of contemporary forest conditions were developed by combining field observations and Landsat imagery and will be central to future work focused on modeling the distribution of spruce-fir ecosystems and associated bird species under different climate change and management scenarios.

Climate-envelope models for black (*Picea mariana*), red (*Picea rubens*), and white spruce (*Picea glauca*) and balsam fir (*Abies* balsamea) were developed by integrating cross-boundary data sources (US and Canada) as well as pre-settlement records of the occurrence of these tree species across the region. Projections of the future distribution of suitable habitat for these species made under RCP6 scenarios using only contemporary data suggest an almost complete loss of suitable habitat for these species from the northeastern United States by 2090, whereas models built with the inclusion of historic data suggest refugia may exist in the high elevations of ME, NH, NY, and VT and high latitude regions of these states. Common climate variables across species for predicting their future distribution reflected the preference for colder climates and wet weather concentrated in the winter months.

Evaluations of the historic location of the ecotonal boundary between high elevation spruce-fir and northern hardwood forests in NH and VT also underscored the importance of accounting for

historic dynamics in these systems as we anticipate climate change impacts. In particular, assessments of the location of this boundary from 1991 to 2010 indicate the upper and lower boundaries shifted downward at rates that averaged -1.5 and -2.0 m/yr respectively, in the Green Mountains, and a mean downward trend of -1.3 m/yr of the upper boundary and no movement of the lower boundary in the White Mountains. These findings are in contrast to broad projections of upslope migration of the ecotone and likely reflect recovery of spruce-fir systems from historic land use and atmospheric deposition impacts.

Our analyses indicated that four bird species considered as ecological indicators for this community, Bicknell's Thrush (*Catharus bicknelli*), Magnolia Warbler (*Setophaga magnolia*), Blackpoll Warbler (*Setophaga striata*) and Yellow-bellied Flycatcher (*Empidonax flaviventris*), each exhibited significant declines. Olive-sided Flycatcher (*Contopus cooperi*), a species of concern in parts of its range, and two additional species for which no previous concern existed, the Evening Grosbeak (*Coccothruastes vespertinus*) and the Gray Jay (*Perisoreus canadensis*), each also showed significant overall declines. Five out of nine species with sufficient data for analyses from Northeast and Great Lakes surveys showed significant differences in trends between these regions. Spruce-fir obligate species were more likely to decline significantly than species that use spruce-fir in addition to other habitat types. These results demonstrate the value of combining disparate data sources for analyzing regional patterns of population trends to confirm and extend conservation concern for some species and identify others for which additional attention may be needed.

Overall, this project has confirmed the vulnerability of spruce-fir ecosystems and associated bird species in demonstrating significant, regional declines of several obligate bird species and projected losses in future habitat under climate change for the dominant tree species constituting these forests. The integration of long-term datasets into our examination of these populations and ecosystems allowed for the detection of important dynamics that may have been obfuscated if only contemporary trends were interpreted. In particular, climate envelope models developed from contemporary forest inventories and historic accounts of spruce-fir occurrence indicate that important refugia for this forest habitat may exist in upper elevation and high latitude areas in northern New England and New York. Similarly, characterizations of recent spruce-fir ecotone dynamics in Vermont and New Hampshire demonstrated downslope movement of these ecosystems over the past several decades; a finding in direct contrast to broad-scale projections for these forest ecosystems. Collectively, these findings underscores the importance of accounting for the broad suite of factors affecting the current and future distributions of forest habitat conditions and associated wildlife species when making projections of the impacts of future climate change. Moreover, the identification of landform and landscape settings where climate refugia are expected to exist, including high elevation and high latitude areas and north-facing slopes, suggests that conservation efforts should continue to protect these areas from incompatible land uses. Future phases of this work will generate fine-scale maps of future spruce-fir refugia that account for the complexity in biophysical conditions and disturbance processes that influence the distribution of this important forest type and its associated species across the study region.

SECTION 4. REPORT BODY:

Purpose and Objectives

The overall purpose of this project was to develop tools and datasets to assist the identification of refugia sites most likely to support spruce-fir forest and its associated high-priority obligate spruce-fir bird species over the long-term under projected climate change scenarios. The communities this project serves are resource managers and planners in the forest and wildlife conservation fields. Specific, original research objectives for this project were: (1) producing high-resolution (temporal and spatial) projections of spruce-fir forests, including stand characteristics like structure and composition; (2) estimating future changes in the distribution, productivity and stand characteristics of the spruce-fir forest type due to potential changes in climate; (3) comparing the distribution and condition of spruce-fir forest for different climate change scenarios to identify areas with key physiographic settings likely to support refugia for this forest type; (4) modeling bird occurrence, distribution, nesting phenology and productivity as functions of climate and these modeled values for forest structure and composition; (5) linking these bird-habitat models to projected climatic and forest conditions to predict future bird occurrence, distribution and nesting phenology and productivity across the region; and (6) identifying areas with the greatest richness of priority bird species across climate scenarios.

Given the broad geographic region addressed with this project and the complexities associated with generating the fine-scale characterizations of forest conditions necessary for predicting refugia, the original six study objectives were modified. Objective 1 was modified to only focus on generating high-resolution maps of current and historic forest structural and compositional conditions for use as initial starting conditions for ongoing and future modeling exercises predicting future habitat under climate change. Objectives 2 and 3 were modified to focus specifically on the dominant tree species found in spruce-fir ecosystems. Objectives 4-6 were highly dependent on the outcomes from the first three objectives and given the time required to generate outputs we modified these final three objective to capitalize on the rich suite of long-term bird data collected as part of this project. As such, Objectives 4 and 5 focused on evaluating long-term population trends in spruce-fir obligate birds to describe regional variation in population trends and to develop and refine climate niche models for these bird species. The resultant models from these objectives will ultimately be applied to the maps of future spruce-fir conditions being generated from this project allowing for assessments of the areas with the greatest richness of priority bird species (original Objective 6, which was eliminated due to length of time required to achieve Objective 1). Despite these modification, the work proposed under the original six objectives is currently ongoing with additional results expected over the next six months.

For Objective 1, we developed a new approach for predicting and mapping forest structural and compositional conditions across our study areas using remote sensing and topographic data. During development of this approach, we also capitalized on historic Landsat and forest vegetation data to characterize the dynamics of montane spruce-fir ecotones in NH and VT and documented widespread downslope movement of this ecotonal boundary despite predictions of predominantly upward movement under climate change. For Objective 2, we assembled 25 long-term forest vegetation datasets into a single database to develop species distribution models for black, red, and white spruce, and balsam fir across ME, NH, NY, VT and eastern Canada. These models were used to project future abundance of these species based on the ENSEMBLE RCP6 with projections indicating a loss of suitable habitat across much of New England and New York by 2090. Examination of these projected shifts under Objective 3 indicated refugia for these species in higher elevations in NH, NY, and VT and in large portions of northwestern ME.

For Objectives 4 and 5, 16, long-term point count datasets from across the Lake States and northeastern United States were assembled and used for estimating regional trends for 14 spruce-fir forest bird species and developing climate niche models. Findings under Objective 4 confirmed population declines for two species previously recognized as species of concern, Bicknell's Thrush and Olive-sided Flycatcher, as well as five additional species, Gray Jay, Yellow-bellied Flycatcher, Magnolia Warbler, Blackpoll Warbler, and Evening Grosbeak. Objective 5 generated comparisons of climate niche breadth and distribution for these species based on published population trends and demonstrated that changes in both realized climate niche breadth and distribution were significantly and positively associated with North American Breeding Bird Survey trends in abundance.

Organization and Approach:
Predicting and mapping forest species composition from multi-season Landsat data and topographic indices (Objective 1)

A central, long-term goal of this project is projecting changes in the distribution of montane spruce-fir forest in New England under different climate change scenarios through the year 2100 using the landscape simulation model, LANDIS-II, to drive these scenarios (Objective 1). Landscape simulation models require maps of initial forest conditions from which to simulate changes in response to processes of succession, disturbance, and climate change. Simulations of future conditions are highly dependent on initial conditions and thus require accurate maps of the spatial distribution of forest species and ages. Current approaches generating maps that realistically reflect the distribution of tree species range from random imputation of forest plot data within landtypes defined by soils and topographic landforms (Landscape Builder, Dijak,2013) to multivariate analysis of hyperspectral satellite data (Foster & Townsend, 2004, Young, et al., 2006) or multi-temporal Landsat TM data (Wolter et al., 1995, Wolter & Townsend, 2011). For this project, we were specifically interested in where potential refugia for spruce-fir forests may develop in the Green and White Mountains of VT and NH and this focus demands maps of current species abundance that have high spatial resolution and accuracy.

We developed a new approach that assigns forest plots into classes based on how similar they are in both below-canopy measures of species abundance, and above-canopy measures of image reflectance, simultaneously. We derived forest community types from a combination of below-canopy forest inventory data and above-canopy measures of seasonal leaf reflectance. We used Canonical Linear Discriminate Analysis and hierarchical agglomeration to cluster classes based on the (dis)similarity in canonical variates. Our goal was to derive community classes that are both useful to forest managers, but that also allow for the most accurate class prediction and mapping from remote sensing and topographic data.

To train our forest classification, we used forest stand-exam inventory data (FVS) from the Green Mountain National Forest, and Landsat TM satellite data from multiple dates and seasons to capture species-specific differences in phenology. Our collaborators at the Green Mountain National Forest provided us with tree-level plot data for 21,687 inventory plots measured between 1976 and 2013. Forest plots only included geographic coordinates starting in 2007. This limited our training data to 1612 georeferenced inventory plots.

As we developed our forest classification and mapping approach, it became apparent that high-elevation spruce-fir forests were undersampled in the georeferenced FVS forest inventory data. As mapping these forest types is crucial to our research questions, we incorporated additional plot data from the Mountain Bird Watch (MBW) dataset that sampled high-elevation sites throughout New England. The inclusion of MBW data (222 additional plots in the Green Mountains) allowed us to capture detailed differences in montane forest species composition, including changes from balsam fir dominance at the highest elevations, to mixes of red spruce, yellow birch and sugar maple at the spruce-fir/temperate forest ecotone. These variations are not captured by any existing forest classification maps for the region.

Predicting future changes in the distribution of the spruce-fir forest type due to potential changes in climate and identifying potential refugia (Objectives 2 and 3)

Twenty five long-term vegetation data sets representing10,493,619 observations on 248,821 plots were collected to provide details about the contemporary distribution of the dominant tree species in spruce-fir ecosystems and allow for the construction of climate envelope models (Appendix A). The data collection period spanned from 1955 to 2012, with the majority collected after 1980 (85%). In addition to these contemporary data, 1,342 historical tree observations from 778 plots were obtained from a database maintained by Charles Cogbill (Cogbill, 2000). This data was originally collected between 1623 and 1869 and represents tree composition at the time of European settlement in the New England states and New York.

Climate data for developing climate envelope models was collected from Moscow Forest Science Laboratory climate database available online at http://forest.moscowfsl.wsu.edu/climate/ (download date 05 January 2014). Climate data was derived by applying thin-plate smoothing spline procedures that extrapolate data from discrete weather stations to specific plot points with corresponding elevation (Rehfeldt, 2006). Current climate data was normalized for a thirty year period (1960-1990) and was based on weather station data for about 15,000 locations for precipitation and 12,000 for temperature (Joyce and Rehfeldt, 2013).

Topographic variables were used to model species occurrence and abundance in order to capture discrete landscape features that influence species' dynamics and life history outcomes, and also to capture effects that terrain features might have on microclimate. Elevation, slope, and aspect data were collected, if available, from the original data source. If not available, elevation data was extracted from the 30 m resolution national elevation dataset (NED) generated by the United States Geological Service (USGS) available at http://viewer.nationalmap.gov/viewer/ (download date 12 February 2013) and from the 30 m resolution digital elevation dataset made available through the Canadian Council on Geomatics (CCOG) available at http://www.geobase.ca/geobase/en/find.do?produit=cded (download date 3 March 2014). Slope and aspect were derived from the NED using the raster package (Hijmans, 2014) available through R statistical software (R Core Team, 2013). Five additional topographic indices were derived from the NED using the System for Automated Geoscientific Analyses (SAGA) (Brenning, 2008), including a topographic wetness index, a convergence index, a terrain index, a topographic openness index, and site curvature. These variables were assumed to capture effects not reflected in the climate variables such as soil drainage, exposure, and solar radiation profiles.

The random forest method was used to construct species-specific presence/absence models with and without historical tree data to evaluate differences with the inclusion of this data. All models were constructed using the random forest algorithm (Liaw and Wiener, 2002) available in R (R Core Team, 2013). Mapped predictions of future distributions for spruce and fir species in northeastern North America were generated using the output of the random forest predicted over different climate landscapes in the years 2030, 2060, and 2090. Mapping was based on 0.00833° (~1 km^2) grid and generated with the raster package (Hijmans, 2014) in R. Future landscapes were acquired for each important variable through the Moscow Forest Science Laboratory's climate database. The ENSEMBLE representative concentration pathways 6 (RCP6) scenario, generated in affiliation with the IPCC was used to forecast future suitable habitat. Different RPCs were created by analyzing varying predicted rates of radiative forcing, as well as greenhouse gases emission rates and concentrations by the year 2100 (Stocker et al. 2013).

Evaluating long-term trends in spruce-fir bird species and relationships between realized climate niche breadth and distribution between 1980 and 2012 (Objectives 4 and 5)

Point count data were obtained from 16 monitoring programs throughout the spruce-fir forest zone of the Midwestern and eastern United States (Fig. 1; Appendix B). Point counts occurred from 1989 to 2013 and were standard single-observer point count surveys. Given that point count data varied across programs in count duration, survey radius, and number of distance sampling categories, we employed the 'QPAD' method (Sólymos et al., 2013a), which uses removal (Farnsworth et al., 2002) and distance sampling (Buckland et al., 2001) methods to control for the effects of survey protocol in the estimation of detection probabilities. The package 'detect' (Sólymos et al., 2013b) in program R version 3.1.2 (R Core Team, 2013) was used to implement the QPAD approach and fit survey data to nine removal and two distance models.

Trends in abundance were calculated for each species and program using a nonlinear regression, implemented in R, with equation $N = ab^yc$, where a is the intercept (abundance at first year of program), b is the slope (trend), y is the survey year, and c is an offset for the detection probability (multiple of p, q, and A) (King et al., 2006, King et al., 2008 and Sólymos et al., 2013a). Trend estimates less than 1.0 indicated a population decrease, estimates greater than 1.0 indicated an increase, and trends equal to 1.0 indicated a stable population. To estimate the regional (Midwest and East) and overall (all programs) trends for each species we used an approach similar to route regression (Geissler and Sauer, 1990 and King et al., 2006), and found the weighted mean (b) of program-level trends using the equation $b = \Sigma(w_i b_i)$. Relative program weights (w_i) were proportional to abundance at the midyear of the program (a_i), length in years of the program (y_i), and inversely by the variance associated with the trend estimate (v_i). So, $w_i = c_i/\Sigma c_i$, where $c_i = a_i y_i/v_i$ (King et al., 2006). 90% CI were estimated for regional and overall trends using bootstrap resampling as described above. We concluded a significant difference in the trends between Midwestern and Eastern regions for a species if the 95% confidence intervals around the difference between these trends did not overlap with 0.00. We used Chi-squared tests implemented in R to determine whether population trends differed between migratory and non-migratory species, or between spruce-fir 'obligates' and 'associates'. Changes in realized climate niche breadth and distribution between 1980 and 2012 were estimated using data from the North American Breeding Bird Survey (BBS) and standard ecological niche modeling techniques. We analyzed changes in niche breadth and distribution in relation to published population trends for these species. Variance partitioning was used to determine the amount of variance in change in niche breadth related to population trend.

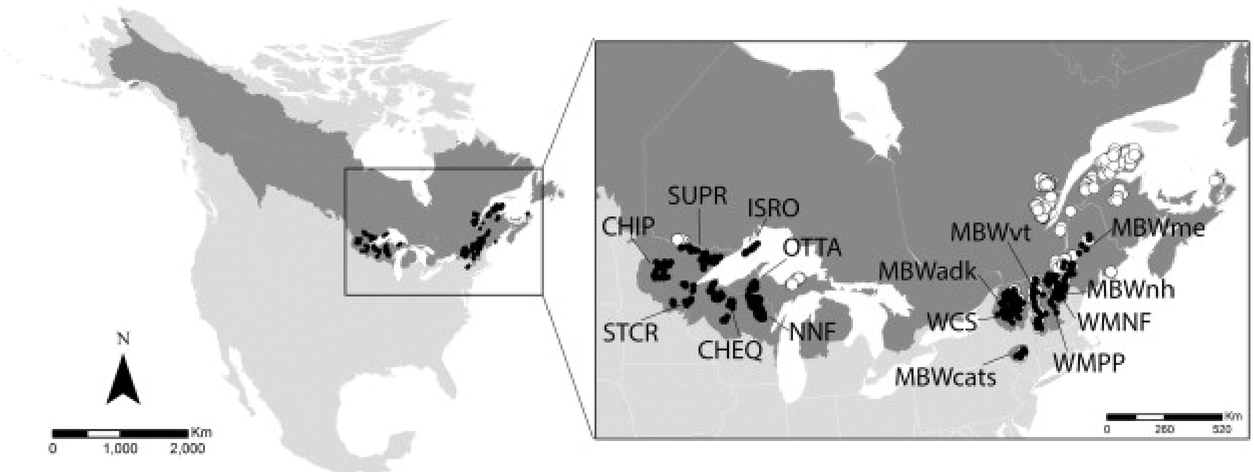


Figure 1. Location of bird point count surveys from Ralston et al. (2015). Dark gray shading is the North American distribution of spruce-fir forests. White circles in inset represent survey locations used to fit detection models, but not used in trend analyses because of insufficient data. Black circles in inset are survey locations used in trend analyses: CHIP = Chippewa National Forest, MN; SUPR = Superior National Forest, MN; STCR = St. Croix State Forest, MN; CHEQ = Chequamegon National Forest, WI; ISRO = Isle Royale, MI; NNF = Nicolet National Forest, WI; OTTA = Ottawa National Forest, MI; WCS = Wildlife Conservation Society, Adirondack Low Elevation Boreal Bird Surveys; MBW = Vermont Center for Ecostudies, Mountain Birdwatch in Adirondacks (MBWadk), Catskills (MBWcats), Green Mountains (MBWvt), White Mountains (MBWnh), and Maine (MBWme); WMPP = White Mountain National Forest PermaPlot Surveys; WMNF = White Mountain National Forest High Elevation Bird Surveys. (See Appendix B for details on surveys).

Project Results, Analysis and Findings:

Predicting and mapping forest species composition from multi-season Landsat data and topographic indices (Objective 1)

The final classification mapped 25 forest communities with a satisfactory users accuracy (63% of plots predicted correctly) considering the degree of species mixing (Figure 2). The models predicted the high-elevation and conifer forest communities that are most important to our work at high rates of accuracy ranging from 70-90%. The largest source of predictive errors occurred due to confusion among plots that differed subtly in mixtures of the most abundant deciduous species: *A. saccharum*, *B. alleghaniensis* and *A. rubrum*, which is understandable as these species do not exhibit strong differences in leaf and canopy spectral reflectance or phenology.

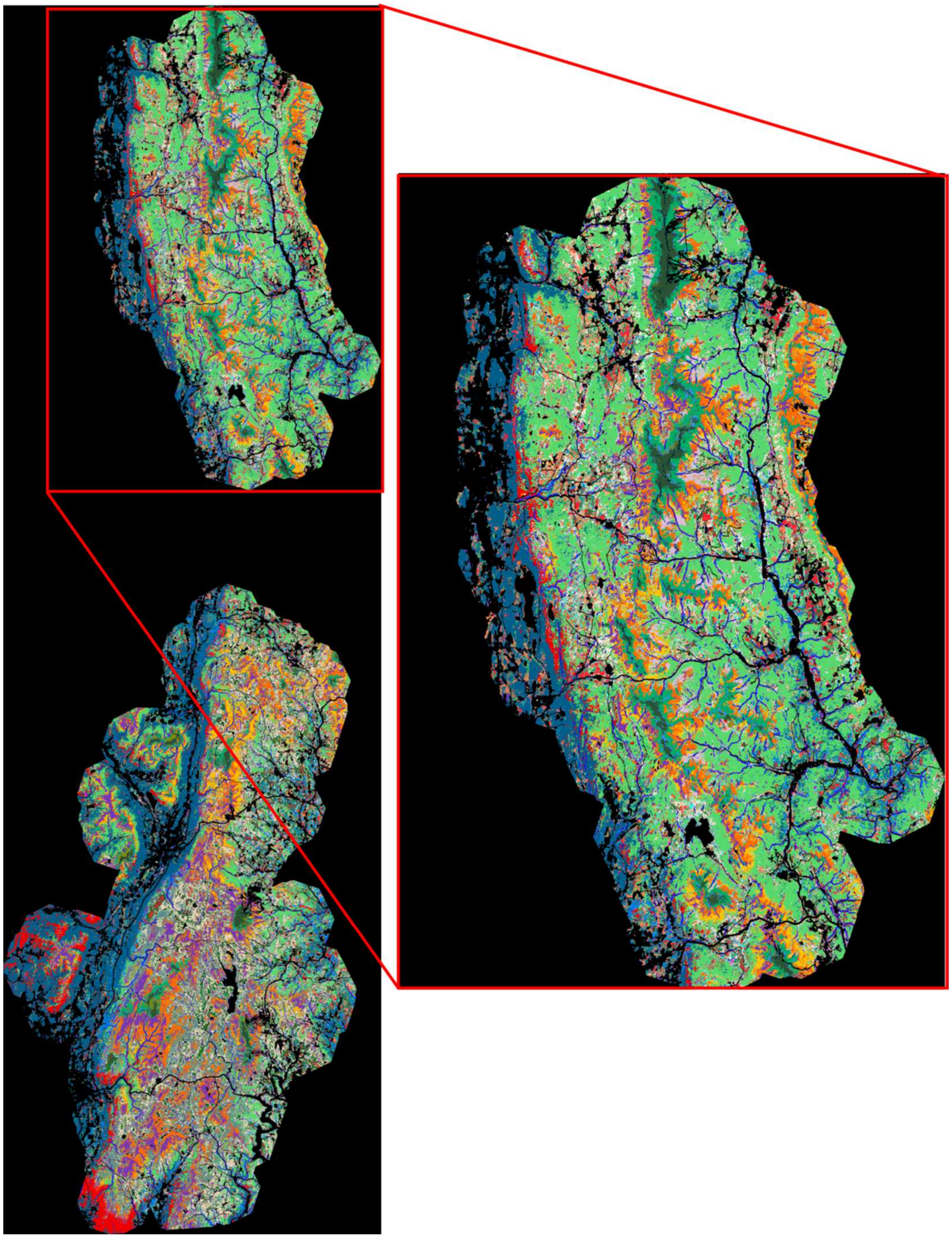


Figure 2. Forest community map of the Green Mountain National Forest and surroundings (5 km buffer beyond forest boundaries). Colors represent 25 forest community types, including high-elevation spruce-fir forest types shown in dark green and blue tones. Black areas are un-modeled landscape or non-forest landuse or water. Spatial resolution is 30 m x 30 m. Area is 1700 km^2.

Other classes that were difficult to predict included uncommon mixes dominated by *Fraxinus ameriana*, *Prunus serotina*, or young forest mixes dominated by *A. rubrum*. Canonical Discriminant Analysis provides class membership probabilities that can be used to determine fuzzy membership for plots that do not belong strongly to a single class. We incorporated posterior membership probabilities to impute FVS plot species and age information to the mapped forest classes to create the initial forest community map for LANDIS-II. As part of our simulation experiment, we will conduct a sensitivity analysis that quantifies how dependent simulation outcomes are on these initial conditions and will quantify the range of outcomes that are possible under different fuzzy membership rules. These results will help quantify a persistent source of uncertainty that propagates into forest landscape simulation model output. We also developed empirical relationships between biomass and basal area for all 24 common species using the GMNF FVS data (Figure 3). These relationships will allow us and our collaborators to compare forest structure data collected using basal area with LANDIS-II simulation outputs that are in biomass units. In addition, we developed an approach for generating climate and soils data at the fine resolutions necessary for predicting refugia in these biophysically complex landscapes (Appendix C).

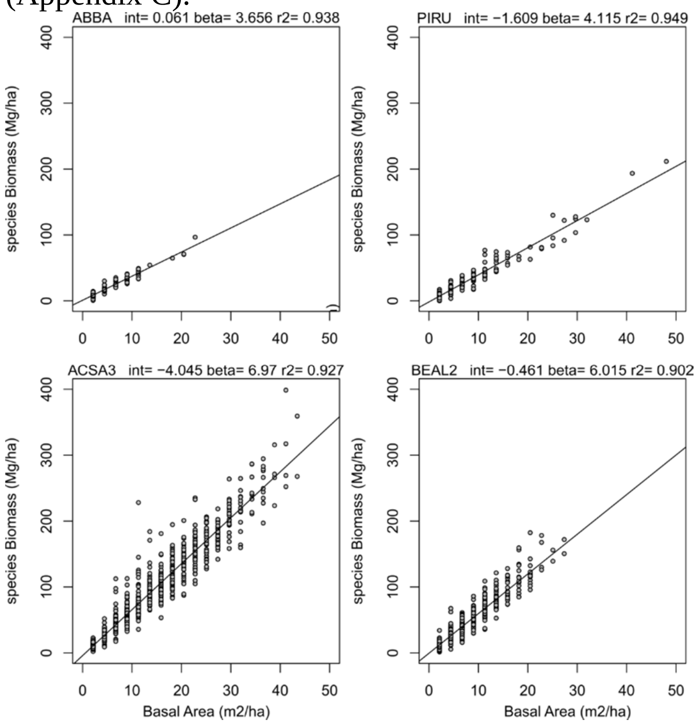
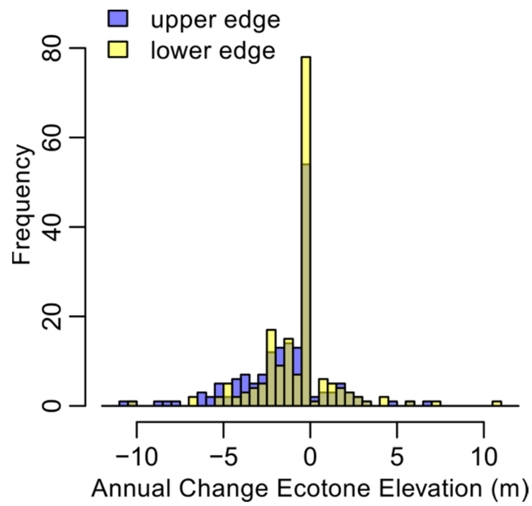


Figure 3. Plot-level basal area summarized by species strongly predicts species biomass, as shown here. Species relationships shown here include *Abies balsamea* (ABBA), *Picea rubra* (PIRU), *Acer saccharum* (ACSA3), and *Betula alleghaniensis* (BEAL).

Application of Landsat imagery collected across the Green Mountain and White Mountains between 1991 and 2010 indicated that movement of the boreal (spruce-fir)-hardwood forest ecotone varied, with the ecotone moving upward on some slopes, downward on others or staying stable (Fig. 4). Downward shifts occurred more frequently than upward shifts. Ecotone edges on 56% and 42% of slopes (upper and lower edges, respectively) moved downward, while only 13% and 15% of slopes had edges that shifted higher. When changes in ecotone elevation were summarized across mountain ranges, both the upper and lower boundaries shifted downward at rates that averaged -1.5 and -2.0 m yr^{-1}, respectively, in the Green Mountains, while only the upper boundary in the White Mountains showed a mean downward trend of -1.3 m yr^{-1}.

Figure 4. Distribution of changes in ecotone elevation estimated for 170 individual slopes over 19 years between 1991 and 2010 (spring) for both the White and Green Mountains. Annual rates of elevation change show that the ecotone moved both up and down at local scales, and often remained unchanged. Differences deemed insignificant according to Tukey's HSD multiple comparison tests were assigned to zero change. From Foster and D'Amato (2015).



Predicting future changes in the distribution of the spruce-fir forest type due to potential changes in climate and identifying potential refugia (Objectives 2 and 3)

Area under receiver operator curve (AUC) values ranged from 0.98-0.99 for models developed for predicting the distribution of the dominant spruce-fir tree species signifying these models were excellent representations of their datasets. Across models, the interactive effects of the ratio of winter precipitation to growing season precipitation and average temperature in the coldest month was an important climate variable for predicting occurrence of black, red, and white spruce, and balsam fir. These findings indicate that areas where winter precipitation matches or exceeds growing season precipitation and mean temperature in the coldest month is lower than the average of the study area are suitable habitat for the species considered in this analysis.

Maps of future habitat suitability generated from these models for the years 2030, 2060, and 2090 under the ENSEMBLE RCP6 model demonstrated shifts north and east in suitable habitat, with the eventual loss of almost all habitat for these species in the U.S. by 2090 (Figure 5). Habitat for the two most common montane species, balsam fir and red spruce, declined to only a few high altitude locations along the Appalachian Mountains in the U.S. by 2090. These include locations in the White Mountains of New Hampshire, and the Longfellow Mountains and Katahdin Mountains of Maine. Within the Acadian Region, further suitable habitat for balsam fir and red spruce was maintained in the northern and coastal highlands of New Brunswick, as well as Cape Breton Island. All suitable habitat for white and black spruce was extirpated from the Acadian Region by 2090. At this time, hotspots for suitable habitat for all four species appear outside the Acadian Region in Québec along the St. Lawrence River Valley and the Gulf of St. Lawrence, including the Gaspé Peninsula and Anticosti Island, and in interior and northern Newfoundland along the northern most reaches of the Appalachian Mountain chain.

The inclusion of the historical tree data made significant differences in the predictions of future suitable habitat for all four species considered in this analysis (Figure 5). The predicted habitat for balsam fir, black spruce, and red spruce all gained additional habitat in 2090 in the U.S., primarily in northern and central Maine, as well as the Adirondacks and the eastern border of Vermont. Predicted suitable habitat for red spruce expanded the most in each time period,

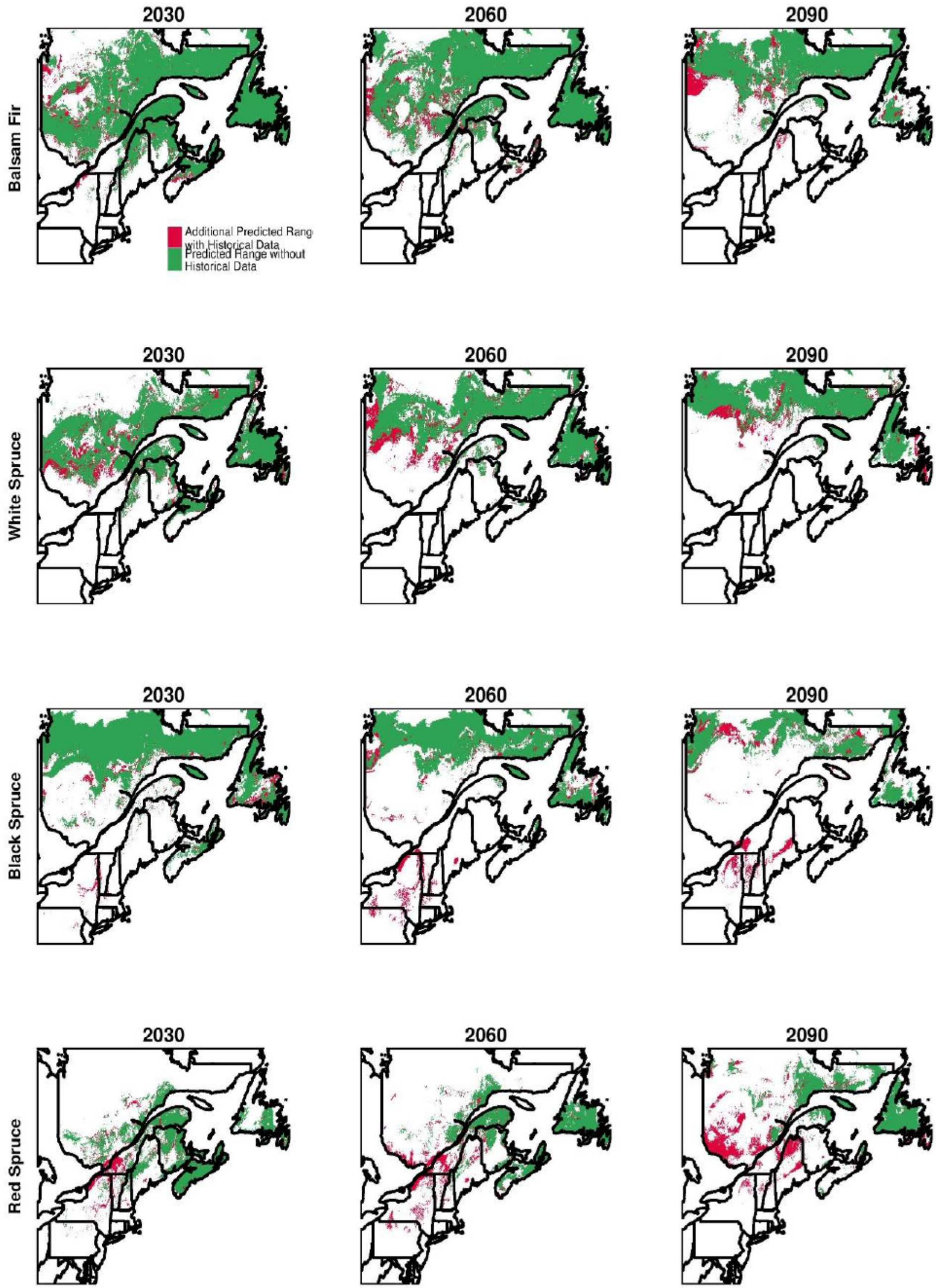


Figure 4. Future predicted presence or absence of dominant tree species constituting spruce-fir forests. Predictions generated in 2030, 2060, and 2090 under the ENSEMBLE RCP6 climate scenario with (red) and without (green) historical data. From Andrews (2015).

followed by black spruce, while white spruce gained the least with the addition of the historical observations.

Evaluating long-term trends in spruce-fir bird species and relationships between realized climate niche breadth and distribution between 1980 and 2012 (Objectives 4 and 5)

Population trend estimates for spruce-fir bird species varied considerably across surveys within each species with the mean range in trend 0.1. Seven of the focal species (50%) demonstrated overall significant declines as determined by weighted means of all program-specific trends and bootstrap estimated 90% confidence intervals (Olive-sided Flycatcher, Yellow-bellied Flycatcher, Gray Jay, Bicknell's Thrush, Magnolia Warbler, Blackpoll Warbler, and Evening Grosbeak), five significantly increased (Red-breasted Nuthatch, Golden-crowned Kinglet, Ruby-crowned Kinglet, Swainson's Thrush, and Palm Warbler), and two exhibited no overall change (Boreal Chickadee and Cape May Warbler, Figure 6). Chi-squared tests indicated significant differences in trends of obligate and associate spruce-fir species ($\chi^2 = 7.00$, df = 2, $P = 0.030$) with greater declines in obligates. A larger proportion of obligates showed overall declines (66.7%) compared with associates (37.5%), and no obligate species showed a significant overall increase, while 62.5% of associate species significantly increased, including Swainson's Thrush. There was no significant difference in the proportion of migratory and non-migratory species showing overall declines ($\chi^2 = 0.63$, df = 2, $P = 0.730$).

Regional trends were significantly different between the Midwestern and Eastern regions for one obligate (Gray Jay), and four associate species (Golden-Crowned Kinglet, Swainson's Thrush, Red-breasted Nuthatch, and Evening Grosbeak). These differences may reflect local and regional variation in environmental stressors, land use history, management practices, and effects of climate change. Our future work linking habitat models that address these stressors with bird population models may help identify the mechanisms underlying population trends and the best management practices for this avian assemblage. Similarly, our analyses of changes in both realized climate niche breadth and distribution indicated these changes were significantly and positively associated with breading bird survey (BBS) trend in abundance. Using variance partitioning, we estimated that 40.6% of the variation in change in niche breadth was explained by population trend, and that 20.0% of this is independent of the influence of changes in distribution. This understanding of how trends in bird populations influence realized climate niche breadth is critical to understanding dynamic species distributions, responses to climate change, and our ability to model future species' distributions in future phases of this work.

Conclusions and Recommendations:

This project has developed a powerful framework and network of collaborators for long-term examinations of the impacts of climate change and other stressors on spruce-fir ecosystems in the northeastern United States and Great Lakes region. Given the complexity of this forest type and bird populations across this broad geographic region, we were unable to achieve all of the original, six project objectives we ambitiously proposed for a two-year project. Nonetheless, this project has developed several science products in the form of peer-reviewed manuscripts on spruce-fir forest and bird species dynamics, long-term vegetation and bird count databases, and fine-resolution maps of current forest conditions that are currently being applied to advance the conservation of these habitats and future research efforts. The remaining objectives that were

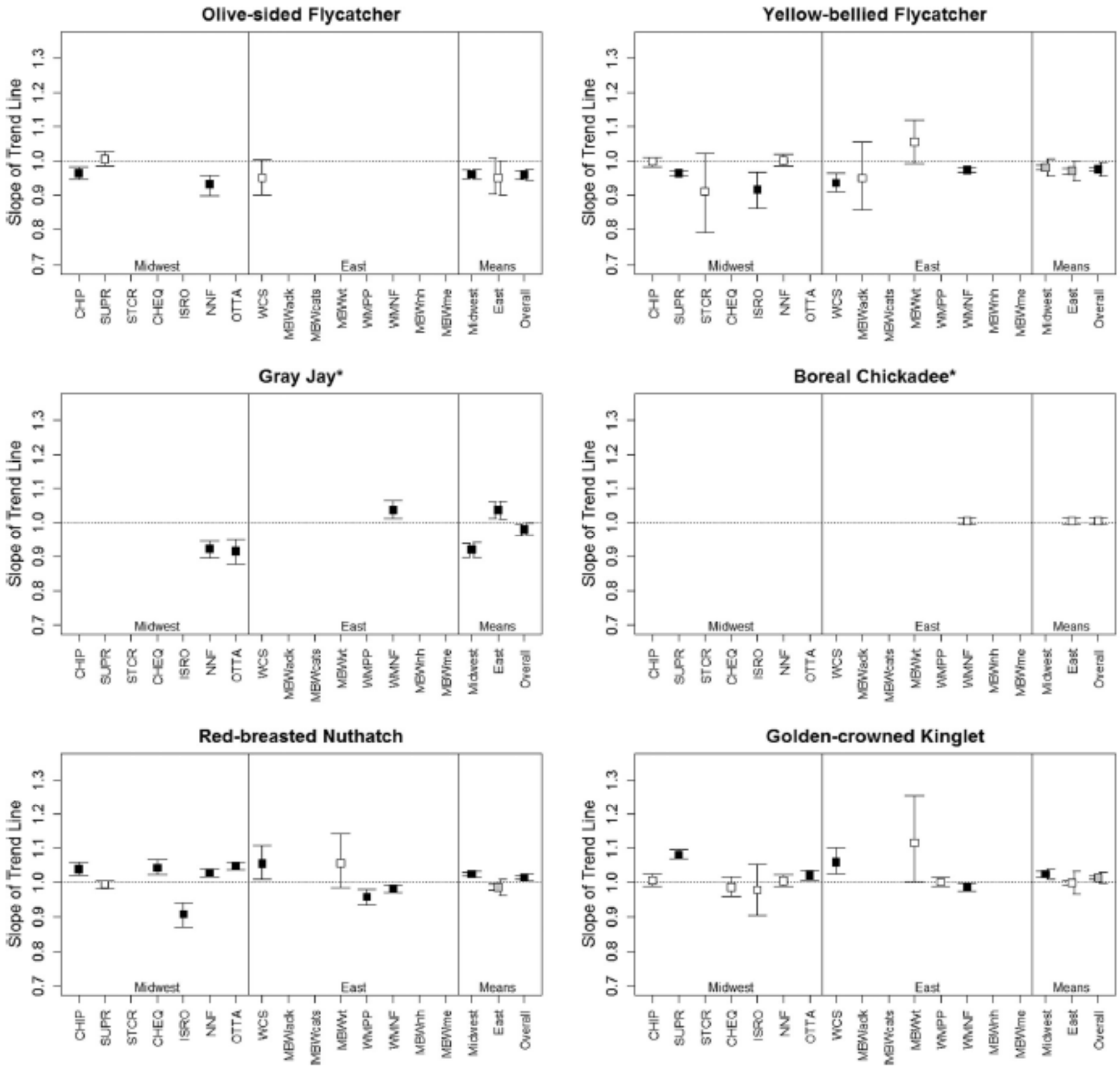


Figure 6. Trend estimates for each species and surveys with a sample size greater than 100 and greater than 50 detections from Ralston et al. (2015). Error bars around Midwest and East surveys represent bootstrap estimated 90% confidence intervals. Error bars around regional and overall mean trends are divided to display both represent bootstrap estimated 90% confidence intervals (left) and propagated uncertainty from survey-level trends (right). Closed black boxes represent significant trends (90% CI do not overlap with 1.0), and open boxes are non-significantly different from 1.0. Gray boxes represent mean trends with 90% CI that do not overlap with 1.0, but that are considered non-significant according to propagated error. Asterisks indicate spruce-fir obligate species. Surveys along X axis are ordered roughly west to east.

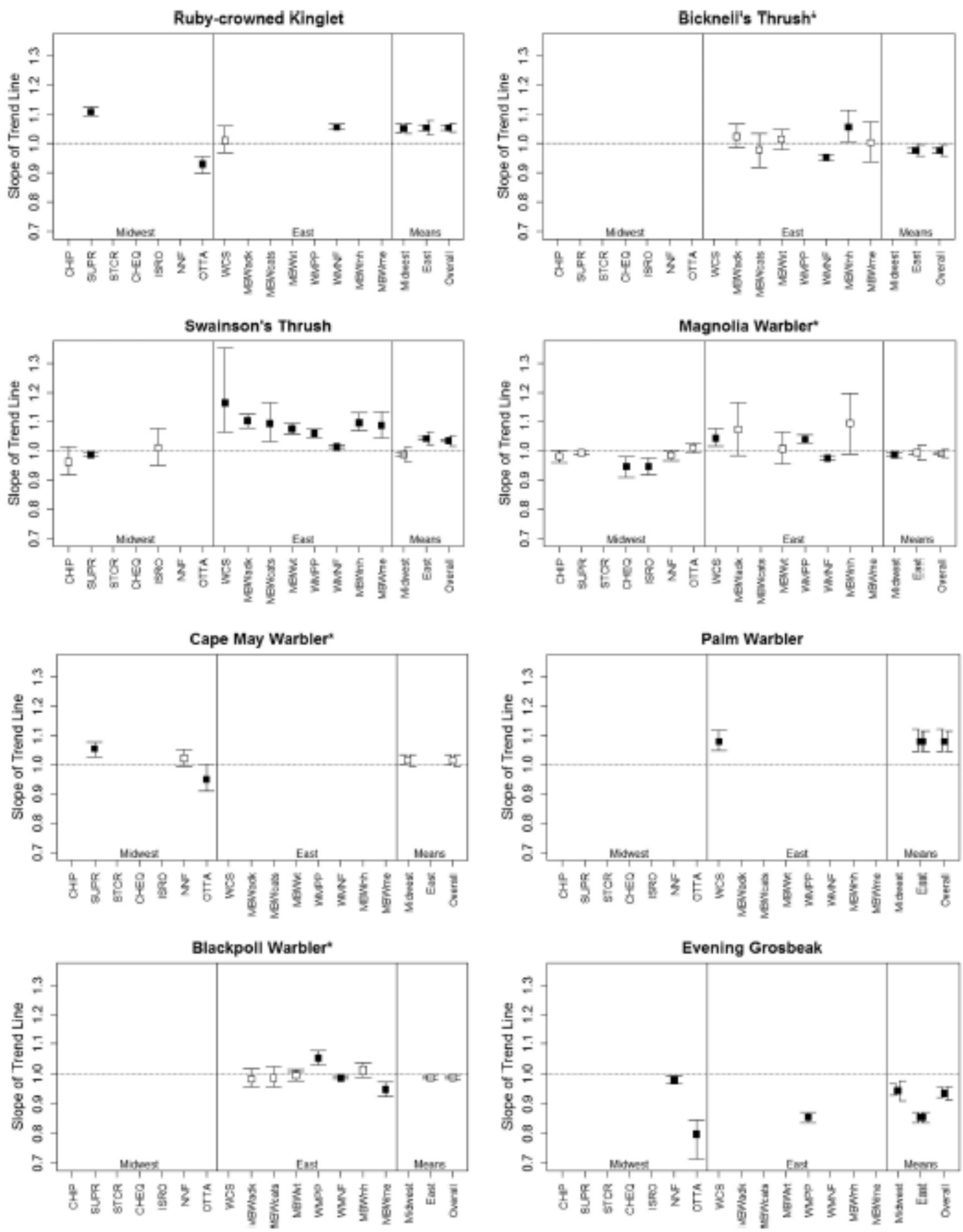


Figure 6. (cont.)

not fully accomplished during the duration of this project are currently being pursued as part of complementary, ongoing projects and are the logical next steps for finalizing maps of spruce-fir refugia for the study region. In addition, this work has been leveraged into additional funding to collect bird population data from montane regions of New England through the Northeastern States Research Cooperative and has resulted in broader collaborations with other wildlife biologists (Dr. Toni Lyn Morelli) to investigate the drivers of spruce-fir wildlife population dynamics over the past several decades. The complexity in forest and bird species dynamics documented by this work highlights the importance of future research that accounts for both fine-scale patterns in forest and bird species behavior and that integrates historical data to fully account for the fundamental climate niche for species now greatly reduced due to past land use. Moreover, future work investigating the effectiveness of different adaptive management approaches at sustaining spruce-fir habitats and associated species is an important direction are research team is taking with this work.

The findings of this work has significantly advanced scientific knowledge regarding the dynamics of montane spruce-fir ecosystems resulting in a recent paper in *Global Change Biology* on the topic (Foster and D'Amato 2015). This work has been integrated into vulnerability assessments for the northeastern United States being led by the Northern Institute of Applied Climate Science and is also being used by managers on the Green Mountain National Forest to assist in prioritization of areas to restore spruce-fir systems. Similarly, this project has generated the most data-rich and detailed examination of avian spruce-fir population trends to date for a large portion of the eastern and Midwestern regions of the United States resulting in a recent publication in *Biological Conservation* (Ralston et al. 2015). This work was able to confirm and extend species-specific conservation concern within the spruce-fir forest community and identify bird species for which additional attention may be needed. Finally, the maps of future distributions of dominant tree species in spruce-fir forests are the first climate envelope models to integrate historical data to elucidate habitats that have been excised by anthropogenic disturbance. These maps indicate that spruce-fir species' habitats are predicted to persist further south in their range under climate change and have been used to inform the abovementioned vulnerability assessments. In addition, these maps highlight the importance of fine-scale projections of future habitat suitability in detecting intra-regional variation in climate response to inform management. Although coarse-scale approaches, such as Tree Atlas, are more readily available and useful for evaluating regional trends, they are not able to detect potential refugia for many of the vulnerable species this project evaluated.

Outreach and Products

Results from this project were shared on numerous occasions with cooperating management organizations (e.g., Green and White Mountain National Forests) and the broader resource management community through scientific presentations at professional meetings, practitioner workshops, and webinars. Products that emerged from this research include:

Articles in preparation, under review, accepted, or published in peer reviewed journals and other non-peer reviewed journals

Foster, J. R., and A. W. D'Amato. 2015. Montane forest ecotones moved downslope in northeastern USA in spite of warming between 1984 and 2011. Global Change Biology 21:4497-4507.

Ralston, J., D.I. King, W.V. DeLuca, G.J. Niemi, M.J. Glennon, J.C. Scarl, and J.D. Lambert. 2015. Combining local-scale survey data to estimate trends in abundance at multiple spatial scales for a threatened community of birds. Biological Conservation 187: 270-278.

Ralston, J., W.V. DeLuca, R. Feldman, D.I. King. *In review*. Realized climate niche breadth varies with population trend and changes in distribution in North American birds. Global Ecology and Biogeography.

Ralston, J., W.V. DeLuca, R. Feldman, D.I. King. *In prep*. Population trends determine ability of North American birds to track climate change. Plan to submit to Global Change Biology in early 2016.

Project-related conference presentations

King, D.I. 2014. Climate change effects on wildlife. Climate Change and Southern New England Forests (Workshop/Training), Northern Institute of Applied Climate Science, Amherst, MA. September 23.

D'Amato, A.W. 2014. Developing forest adaptation strategies for northern forests in an uncertain future. Northeast Climate Science Center Webinar Series. October 1.

Foster, J. R., and A. W. D'Amato. 2014. Modeling effects of climate change on spruce-fir forest ecosystems: Changes in the montane ecotone between boreal and temperate forests in the Green Mountains, U.S.A, from forest edge detection in Landsat TM imagery,1989 to 2011. American Geophysical Union Fall Meeting, San Francisco, CA. December 15-19.

Simons-Legaard, E., K. Legaard, A. Weiskittel, C. Andrews, and A.W. D'Amato. 2015. Future distribution and productivity of spruce-fir forests under climate change in Maine: implications for forest management practices. Maine Sustainability and Water Conference, Orono, ME. March 31.

D'Amato, A.W. 2015. Something old, something new: silvicultural strategies for addressing climate change. Invited talk at the New England Society of American Foresters Annual Meeting, Farlee, VT. March 26th.

D'Amato, A.W. 2015. Current and future forest habitats in New England. Moose, Boreal Forest, and Climate Change Workshop. Wildlife Conservation Society, Westborough, MN. February 4.

Foster, J.R., A.W. D'Amato, and J.B. Bradford. 2015. Simulation of insect impacts on forest dynamics: Landsat defoliation maps predict growth declines in tree ring data. International Association for Landscape Ecology World Congress. Portland, OR. July 9.

Communications with decision-makers

This work involved close cooperation with the Green Mountain and White Mountain National Forests to obtain long-term forest vegetation data from these respective National Forests. To this end, we met with staff on the Green Mountain National Forest (Diane Burbank, Jeff Tilley, and Jay Klink) on July 31, 2014 and White Mountain National Forest staff (Jeff Williams, Lesley Rowse, Jessie Dubuque, Gail Wigler, Reggie Gilbert, and Ashton Hargrave) on November 12, 2014 to discuss their information needs from this project. Additional discussion of the project with White Mountain National Forest staff (Roger Boyer and Leighlan Prout) occurred on August 18, 2015. To assist our cooperators with collection of long-term vegetation data, we hired a seasonal biological technician, Kaylee Nelsen, who assisted National Park Service Great Lakes Network Office staff (Suzanne Sanders) in collecting data from long-term monitoring plots at Grand Portage National Monument (Summer 2014). Finally, we continue to coordinate our work with the Wildlife Conservation Society, namely Dr. Erika Rowland, and the National Climate Change and Wildlife Science Center to generate model projections that can be used to assist in scenario planning related to moose conservation in northeastern North America under climate change. Findings from our work were presented at a meeting associated with this effort and used to assist with scenario planning for future moose habitat in New England and portions of New York. In addition, findings from this work were used to help inform vulnerability assessments for spruce-fir ecosystems as part of the New England Climate Change Response Framework being led by the Northern Institute of Applied Climate Science (December 2 and 3, 2015).

Other products

Andrews, C. 2015. Modeling and forecasting the influence of current and future climate on eastern North American spruce-fir (Picea-Abies) forests. Master's Thesis, University of Maine, Orono. 180 pp.

Long-term forest vegetation database for spruce-fir forests in the Northeastern US. (see Appendix A).

Long-term bird monitoring database for spruce-fir forests in the Northeastern US. (see Appendix B).

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APPENDICES

Table A.1. Long-term forest vegetation datasets used for developing climate envelope models and maps of spruce-fir forest conditions.

Source	Owner	Geographic Region	Number of Observations	Number of Plots	Remeasurement Interval (years)	Measurement Period	Plot Size (ha)/Prism[a]	% of Plots with Spruce or Fir
Forest Inventory and Analysis (FIA)	US Forest Service	Eastern US	6,833,159	194,838	Varies	1968-2010	0.07[b]	0.50%
Québec PSP	Québec Ministry of Natural Resources	Southern Québec	1,583,176	39,436	5	1970-2013	0.04	84.5
Nova Scotia PSP	Nova Scotia Department of Natural Resources Forestry Division	Nova Scotia	494,108	3,042	5	1965-2006	0.04	94.7
New Brunswick PSP	New Brunswick Department of Natural Resources.	New Brunswick	493,104	2,387	5	1985-2005	0.04[c]	94.1
Québec Research PSP	Québec Ministry of Natural Resources	Southeast Québec	321,855	3,069	5 to 11	1970-2008	0.32 - 0.40	88.7
Newfoundland PSP	Newfoundland Forest Service	Newfoundland	321,550	1,291	4 or 5	1985-2008	0.04[d]	100
Penobscot Experimental Forest[e]	US Forest Service	Central Maine	169,118	562	Varies	1974-2008	Varies	98.2
Commercial Thinning Research Network	Cooperative Forestry Research Unit	Northern ME	80,035	78	1 or 2	2000-2007	0.08	100
Brann GIS	University of Maine	Northern Maine	64,570	365	1	1975-1985	0.04	100
AFERP	University of Maine	Central Maine	31,850	180	5	1995-2007	0.01 or 0.05	98.9
Prince Edward Island PSP	Prince Edward Island Department of Agriculture and Forestry	Prince Edward Island	26,782	691	-	1999 - ?	-	91.3

Table A1. (cont)

Source	Owner	Geographic Region	Number of Observations	Number of Plots	Remeasurement Interval (years)	Measurement Period	Plot Size (ha)/Prism[a]	% of Plots with Spruce or Fir
Caroline A. Fox Research Forest	New Hampshire Division of Parks and Lands	Southern New Hampshire	20,118	65	10	1955-2011	0.08	33.3
Vermont Forest Health Monitoring	Vermont Monitoring Cooperative	Vermont	17,065	76	1	1992-2013	0.06	63.2
Northeast Temperate Network	National Park Service	Northeastern US	14,532	324	4	2006-2013	0.02 or 0.04[f]	40.7
Austin Pond	Cooperative Forestry Research Unit	Central Maine	10,267	207	-	1999	0.02	100
Mountain Birdwatch Program	Vermont Center for Ecostudies	High elevations in New England and New York	5,797	2,008	1	2010-2011	10 BAF prism	99.4
Big Reed Forest Reserve	University of Maine	Central Maine	3,102	37	-	2000-2001	0.15 or 0.25	97.3
New Hampshire Forest Health Monitoring	New Hampshire Division of Parks and Lands	New Hampshire	2,939	16	1	2003-2013	0.06	100
High Elevation Bird Habitat	University of Massachusetts	High elevations in New England and New York	1,752	151	1	2011-2013	0.04	94.7
Witness Tree Data	Database maintained by Charles Cogbill	New England and New York	1,342	778	-	1623-1859	NA	72.6
McCormack Thinning Study	Cooperative Forestry Research Unit	Northern Maine	691	14	NA	1978-1994	1	100

Table A1. (cont)

Source	Owner	Geographic Region	Number of Observations	Number of Plots	Remeasurement Interval (years)	Measurement Period	Plot Size (ha)/Prism[a]	% of Plots with Spruce or Fir
Quabbin Reservoir CFI	Massachusetts Department of Conservation and Recreation	Central Massachusetts	456	5	5 or 10	1960-2010	0.08	80
HoneyBrook	New Hampshire Division of Parks and Lands	Southern NNew Hampshire	38	5	-	2013	20 BAF prism	100

[a] Majority or most frequent plot sizes reported

[b] Sampling design for FIA implemented in 1998. Prior to this data sampling designs varied by region and were taken into account in analyses.

[c] Plot size varied by tree density. 80% of plots were 0.04 ha in size. The remaining 29% varied from 0.0008 to 0.02 ha in size (NB)

[d] Plot size varied by tree density. 34% of plots were 0.04 ha in size. The remaining 66% varied from 0.1 to 1 ha in size

[e] Data from numerous studies within the Penobscot Experimental Forest were used including a continuous forest inventory (CFI), a long term pre-commercial thinning study (PCT), and the research of Dr. Mike Saunders.

[f] 0.02 ha plots at Acadia National Park. 0.04 at all other National Parks in the Network.

APPENDIX B

Table B1. Survey protocol for bird monitoring programs used in this project. Programs with at least two time intervals were used removal models and those with at least two distance intervals were used in distance analyses. Programs with greater than five years of data were used in trend analyses.

Monitoring program	*State/ Province*	*Abbrev.*	*Overseeing organization*	*Years of survey*	*# of survey points*
Chippewa National Forest	MN	CHIP	U.S. Forest Service	1991-2013	420
Voyageurs National Park	MN	--	National Parks Service	2010-2013	80
Superior National Forest	MN	SUPR	U.S. Forest Service	1991-2013	600
St. Croix State Forest	MN	STCR	U.S. Forest Service	1992-2003	203
Chequamegon National Forest	WI	CHEQ	U.S. Forest Service	1992-2010	407
Isle Royale	MI	ISRO	National Park Service	2006-2013	130
Nicolet National Forest	WI	NNF	U.S. Forest Service	1989-2012	317
Ottawa National Forest	MI	OTTA	U.S. Forest Service	1991-2013	104
Pictured Rocks National Lakeshore	MI	--	National Parks Service	2011-2013	52
Adirondack Low Elevation Boreal Bird Surveys	NY	WCS	Wildlife Conservation Society	2003-2013	440
Mountain Birdwatch 1.0	NY, VT, NH, ME	MBW	Vermont Center for Ecostudies	2003-2010	893
Mountain Birdwatch 2.0	NY, VT, NH, ME, QU, NB, NS	--	Vermont Center for Ecostudies	2010-2013	1869
DeLuca (2013)	NH	--	University of Massachusetts	2006-2007	103
White Mountains Perma Plot Surveys	NH	WMPP	White Mountain National Forest	1992-2012	360
White Mountains High Elevation Bird Surveys	NH	WMNF	White Mountain National Forest	1993-2013	905
Northeast Temperate Network, Acadia National Park	ME	--	National Park Service	2007-2013	51

APPENDIX C

Soils and climate for simulating the future distribution of spruce-fir forests – data sources and analyses

Identification of potential refugia for this locally rare forest type requires that input data have adequate spatial resolution to capture variation that is important to spruce-fir persistence in the landscape. For this reason, we are using the PRISM gridded climate dataset to characterize current and historical climate (monthly data @ 2.5 arc-second or ~ 4 km resolution), and the NASA Earth Exchange (NEX) Downscaled Climate Projections (NEX-DCP30) dataset for the coterminous U.S. for our climate change projections (Figure C1). NEX data include CMIP-5 projections statistically downscaled at 30 arc-second or ~ 800 m resolution. Capturing the variation in temperature that results from the vertical lapse rate in mountainous terrain is critical for our purposes, as cooler mountain peaks are not represented at coarser spatial resolutions. We are running simulations using projections from five GCMs under RCP 4.5 and RCP 8.5 to capture a range of future climate scenarios.

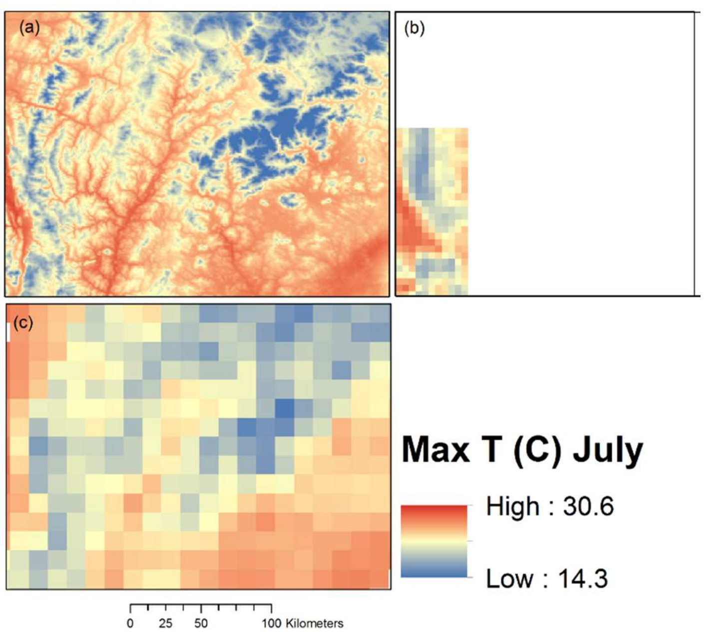

Figure C1. Comparison of gridded climate data from three different sources at three different spatial resolutions. Maximum July temperature is displayed at ~ 1 km resolution in the downscaled NEX data from the CCSM4 model (a), max July temperature over the GMNF study area only is shown for the PRISM historical climate data at ~ 4 km resolution (b), and max July temperature is shown for the study area from downscaled CMIP5 data at ~ 8 km resolution for the HADGEM2 GCM (Maurer dataset). Fine-scale variation in temperatures is evident at each resolution, but fine-scale patterns are lost as resolution gets coarser.

The spatial distribution of soils with different soil properties is the other major driver of the variation in growth and establishment rates among tree species. We downloaded SSURGO soils data for all the counties in Vermont and two counties in Massachusetts that overlapped with the GMNF buffer area. SSURGO soils data contain the most detailed and up to date spatial information on soil properties from the US soil survey. We felt it was important to capture soil variation at the finest spatial resolution possible, but SSURGO data present some unique challenges to landscape-level analyses. The main challenge is that when soil characteristics are summarized throughout the soil horizons and across polygons of the same type, discontinuities across counties become very apparent and can create false patterns in landscape model inputs and results. These county-level discontinuities do not represent actual differences in soils but rather reflect differences among methodologies used by different soil scientists and administrative units. While this is not a simple problem to correct, we developed an approach to effectively normalize summarized soils variables across counties through a combination of quantile analysis and isodata classification. The end result was a classification of 31 soil ecoregions that were clustered based on similarities in soils and topographic position including sand, silt, clay, organic matter, available waterholding capacity, field capacity (3rd bar), wilting point (15bar), ph, depth to bedrock, elevation and slope (Figures C2 and C3).

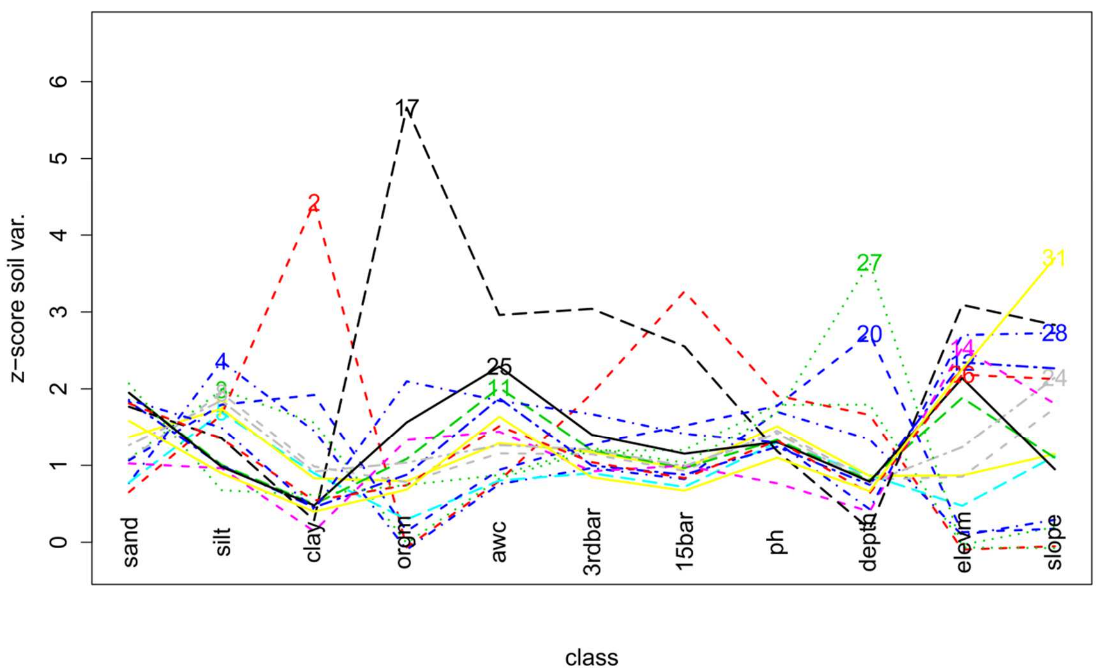

Figure C2. Standardized class means across 11 dimensions for 31 soil ecoregions derived from SSURGO soils data (summarized by MUKEY down to 50 cm depth) and NED DEM data. We can see that soils class 17 is a high-elevation class with high organic matter content, but shallow soil depth, while class 2 occurs at low elevations and has high clay content.

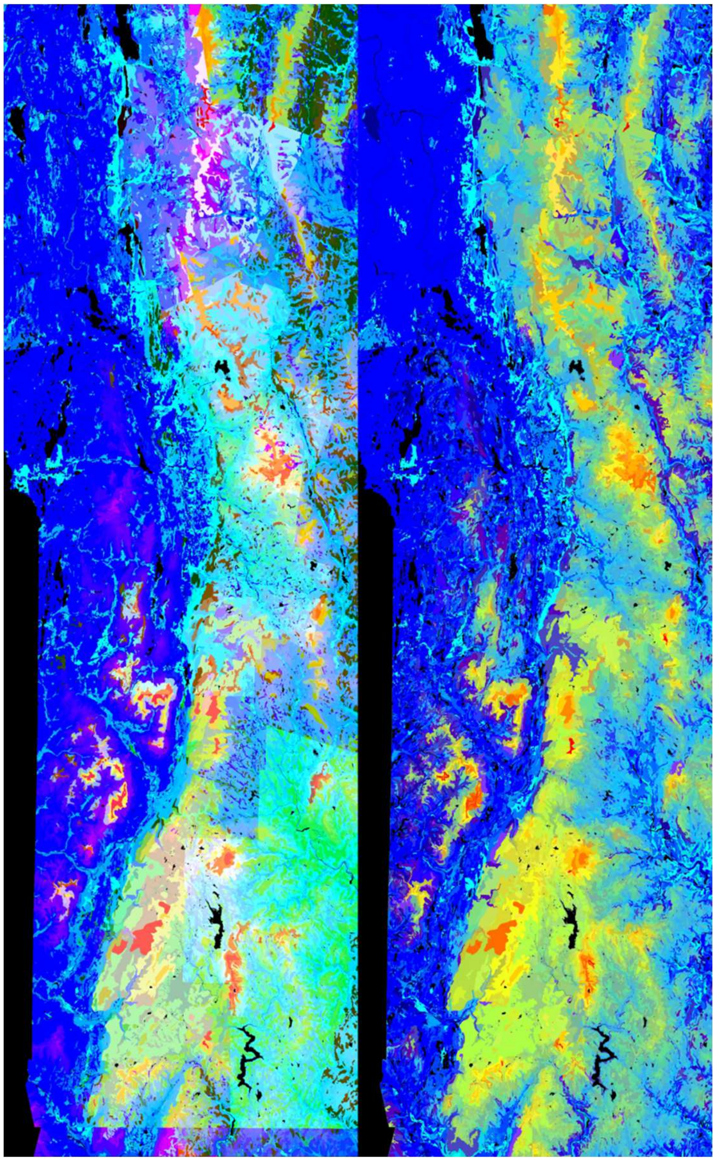

Figure C3. Raw SSURGO soils data covering the Green Mountains, VT (left), summarized by MUKEY and corrected SSURGO data that has been normalized to correct for discontinuities across county borders (right). Map shows a red-green-blue (RGB) display of elevation (red), percent sand (green), and ph (blue). Yellow to orange colors show sandy, high-elevation soils that are more acidic while blues are lower elevation, less sandy, basic soils.